Use of DFT-Based Reactivity Descriptors for Rationalizing Radical Reactions: A Critical Analysis

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Hydrogen abstraction by C_2H, OH, CH_3, CF_3, C_2H_3, and C_2H_5 radicals from methane and propene and addition reactions of these radicals with substituted propenes have been investigated by using BHandHLYP/6-311G-(d,p) level of theory. Transition states for all these reactions have been located. The reactivity of different radicals and substrates toward hydrogen abstraction and radical addition reactions has been critically analyzed by using density functional theory based reactivity descriptors, namely, local softness and electronegativity. The regiochemistry of the radical addition reaction has also been explained from the local softness values of the potential addition sites.

1. Introduction

Thanks to the pioneering works of Parr and co-workers, DFT has been found to be the source of many interesting derivations allowing rationalization of previously ill-defined but useful concepts in chemistry.[1] For example, the hard and soft acids and bases (HSAB) principle introduced by Pearson in 1963 has long been playing a useful role in understanding the behavior of many chemical systems.[2] But the major criticism of the principle was that no rigorous definition of hardness existed at that time. However, in 1983 Parr and Pearson gave that much needed quantitative definition of hardness

$$\eta = \frac{1}{2}\left(\frac{\partial^2 E}{\partial N^2}\right)_v$$

where E and N are the energy and number of electrons in a system and the derivative is taken at the fixed external potential, ν, of a system and at the same time provided a simple proof of the HSAB principle.[3] Further justification of the HSAB principle came from the later work of Parr and co-workers.[4] The concept of electronegativity (χ) has also been an important qualitative tool for chemists since the beginning of quantum theory. However, due to the lack of a rigorous definition, many empirical electronegativity scales were defined time to time by using different molecular properties (such as gas-phase bond energy, ionization energy, electron affinity etc.).[5−7] The newly developed electronegativity scale of Luo and Benson[7] has been found to correlate well with heats of formation for many series of compounds. They also observed[8] a good linear correlation between electronegativity and intrinsic Lewis acid strength of main group elements. The rigorous definition of electronegativity [$\chi = -\mu = -(\partial E/\partial N)_v$] came only in 1980s from the work of Parr and Pearson,[1] where electronegativity was defined as the negative of the chemical potential (μ) of the system. Hardness, softness ($S = 1/\eta$), and electronegativity all are global parameters of a system and they reflect the overall electronic nature and reactivity of a system but do not provide any information about local reactivity.[3]

The determination of the specific sites of interaction between two chemical species is of fundamental importance in establishing the mechanism of reaction and also for designing desired products. A number of local reactivity parameters, such as Fukui functions[9] and local softness[10] have also been derived from DFT to determine the specific sites of interaction between two reagents. These parameters are associated with the response of the electron density of a system to a change in number of electrons (N) or external potential [$v(r)$]. Thus they are directly related to the inherent reactivity of a chemical species toward different types of chemical reagents. Generally, it is believed that the larger the value of the Fukui function the greater the reactivity. These local reactivity descriptors were used for the interpretation of a wide range of chemical problems. Using appropriate condensed-to-atom Fukui function or softness, we have determined the preferred site of attack in [2+1][11] and [2+2][12] addition reactions. These descriptors were also used for interpreting the mechanism of other types of reactions.[13] Recently, the Fukui function was also applied for the prediction of gas-phase proton affinities.[14] Chatterjee et al. determined the most reactive site in zeolite for absorption of molecules from the Fukui function values of different potential sites.[15,16] Roy used local softness for the interpretation of the mechanism of nucleophilic substitution reaction to alkyl halides.[17] A detailed analysis of these local reactivity descriptors and its applicability to various chemical problems can be found in the recent reviews.[18]

Now with the introduction of local reactivity parameters (such as Fukui functions [$f(r)$] and local softness [$s(r)$]), Gazquez and Mendez put forward a local version of the HSAB principle.[19] They proposed that the interaction between two chemical species takes place mostly through atoms of approximately equal softness. The proposition has been found to be successful in

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resolving the regioselective behavior of various types of addition reactions. Based on the local HSAB principle, a softness matching criteria was proposed by Chandra, Nguyen, Geerlings, and co-workers[12,20−24] for understanding the regioselectivity of cycloaddition reactions, in particular for rationalizing the regiochemistry of various types of 1,3-dipolar cycloaddition (13DC) reactions. Later Ponti[25] provided further theoretical justification of the softness matching criteria used for explaining the regiochemistry of cycloaddition reactions. He also proposed a method for calculating the change in grand potential ($\Delta\Omega$)[26] from the local softness values of the interacting atoms and the chemical potentials of the two reactants. This change in grand potential can be used to predict quantitative regioselectivity by estimating the branching ratios of possible reactions.[27,28] Interestingly Ponti's procedure differs from the local HSAB principle of Gazquez and Mendez in the case of [2+1] addition reaction. According to Ponti,[25] the softest atom between the two sites should be the most favored site of attack, whereas local HSAB principle says bond formation is preferable between the atom pair with the closest softness. In some cases, these two procedures may present a conflicting picture. We feel that more critical analysis is required to find out which one is better for the understanding of regiochemistry.

In any case, it is clear from the above discussion that DFT-based reactivity descriptors have been successfully used in a wide variety of reactions for the qualitative interpretation of reaction mechanism, site-selectivity, and regiochemistry. Moreover, these reactivity descriptors have also been used for the quantitative predictions of proton affinity and branching ratios in multichannel chemical reactions.[14,27,28] Unfortunately, however, applicability of these descriptors has hardly been judged for an important class of reactions, namely, radical reactions. To our knowledge, so far there is only one preliminary work from our group where local reactivity indices were used to determine the regioselectivity of free radical addition to olefins.[29] It was observed that radical attack preferentially takes place to a carbon atom with the highest value of softness for radical attack (s^0). Of course, there have been numerous attempts to rationalize theoretically the mechanism of free radical addition using the conventional molecular orbital calculations. We do not intend to discuss the merits/demerits of those approaches here. Instead, our main objective is to analyze critically whether DFT-based local reactivity descriptors can be used to predict the reactivity in different types of radical reactions. To this end, we have studied two important sets of reactions: (i) hydrogen abstraction reaction of methane (CH_4) and propene ($H_2C{=}CHCH_3$) with a series of free radicals and (ii) radical addition reaction of propene by a series of free radicals. Finally, addition and hydrogen abstraction reactions of some substituted propenes with OH and CH_3 radicals have also been considered to judge further the applicability of the DFT-based reactivity descriptors in elucidating the regiochemistry of addition.

2. Computational Details

DFT calculations were performed by using the Gaussian-98 suite of programs.[30] We must emphasize here that our objective here is not to produce very accurate potential energy surfaces for these reactions. But at the same time, the method employed should be good enough to produce the right trend for the barrier heights for a series of reactions and thereby the correct regiochemistry. To this end, the BHandHLYP functional[31] was used along with the standard 6-311G(d,p) basis set. Our choice of this unusual functional (BHandHLYP) was based on the extensive studies made by Zhang et al.[32] and Durant[33] and also the recent study by Pritchard et al.[34] They concluded that this functional gave good overall performance in predicting geometry, vibrational frequencies, and barrier heights for proton-transfer reactions and radical reactions. The geometries of the radicals (OH, CH_3, CF_3, C_2H, C_2H_3, C_2H_5, C_3H_6), CH_4, propene, and substituted propene molecules ($H_3C{-}CH{=}CHX$, X = F, Cl, NH_2) were first fully optimized at the said level of calculations. Then transition states (TSs) for the hydrogen abstraction reactions of methane and propene with radicals ($R{-}H + \cdot R' \rightarrow R'{-}H + {}^\bullet R$) were determined. Similarly, we located the TSs for the addition reactions of radicals to both the doubly bonded carbon atoms of substituted propenes. The classical barrier height for each reaction was calculated from the energy difference between the TS and the reactants. The regioselectivity of the radical addition reactions were determined from the barrier heights of addition to the C_α and C_β carbon atoms of propene (see Figure 1), because the reaction path with the lower barrier height is likely to dominate the addition reaction. To check the accuracy of our DFT results for barrier heights, we determined the barrier heights also by employing a high a level of ab initio theory, namely, the CCSD(T)/6-311++G(d,p) method. However, BHandHLYP results were found to be close to the CCSD(T) results and they follow the same trend. The correlation between the barrier heights calculated by using the CCSD(T) and BHandHLYP methods are shown in Figure S1, which is given as supplementary information.

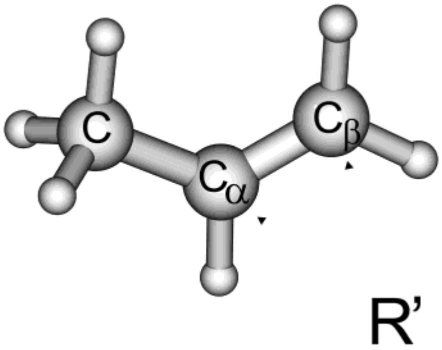

Figure 1. Schematic representation of the two possible sites ofattack for radical addition to propene.

The DFT-based global reactivity descriptors, such as electronegativity (χ) and softness (S) were computed from the finite difference formulas:[1]

$$\chi = -\mu = (\mathrm{IE} + \mathrm{EA})/2 \quad \text{and} \quad \mathrm{S} = 1/(\mathrm{IE} - \mathrm{EA})$$

where IE and EA are the first vertical ionization energy and electron affinity, respectively, and μ is the chemical potential of the system. The IE and EA were computed from the ΔSCF procedure, i.e., by performing separate SCF calculations for the neutral, cationic, and anionic species of a system. The Fukui function is defined as the response of the electron density to the change in total number of electrons [$f(r) = (\partial\rho/\partial N)_v$], and the local softness can be expressed as $s(r) = S{\cdot}f(r)$. The condensed to atom (X) softness value[35] for radical attack was calculated from the finite difference formula as

$$s^0(\mathrm{X}) = 0.5S[q(N+1) - q(N-1)]$$

where $q(N-1)$ and $q(N+1)$ are the electron population for the atom X in the cationic and anionic species of a system, respectively. The electronic populations of atoms were evaluated following the Merz−Kollman (MK) procedure.[36] This scheme

TABLE 1: Global Softness (S, au^{-1}), Electronegativity (χ, eV), Atomic Softness for Radical Attack for the Interacting Atom of Different Radicals [s^0(X)], and Classical Barrier Heights for Hydrogen Abstraction from Methane and Different Sites of Propylene

				barrier heights, kJ/mol[a]			
					$H_3C{-}C_\alpha H{=}C_\beta H_2$		
radical	S[b]	c	s^0(X)[c]	CH_4	C−H	C_α−H	C_β−H
OH	1.70	7.93	1.410	42 (34)	22 (15)	37 (29)	47 (38)
CH_3	2.46	4.15	3.207	82 (81)	61 (58)	81 (77)	90 (86)
CF_3	2.23	5.30	2.720	70 (61)	49 (38)	69 (57)	78 (66)
C_2H	2.33	8.21	1.028	3 (2)	−0.5 (−1)	2 (−1)	6 (1)
C_2H_3	2.63	4.44	2.596	62 (57)	42 (35)	60 (52)	69 (61)
C_2H_5	2.71	3.45	2.942	91 (89)	68 (64)	90 (85)	99 (94)

[a] The quantities within bracket are the barrier heights after zero-point energy corrections. [b] S values for CH_4 is 1.52 au^{-1}. [c] X is O atom in OH and C atom in other hydrocarbon radicals.

has been shown to be reliable[37,38] and also used in most calculations of regiochemistry.[22,23,27,39]

3. Results and Discussion

The structures of the TSs for hydrogen abstraction and radical addition reactions for the systems studied here along with the other results regarding the potential energy surfaces of these reactions will be discussed elsewhere. Here we wish to focus mainly on the reactivity aspects of different radicals and substrates, such as methane and propene, toward hydrogen abstraction and radical addition reactions.

A. Hydrogen Abstraction Reactions. The classical barrier heights and the barrier heights with zero point energy corrections for hydrogen abstraction by different radicals from methane and also from three different sites of propene ($H_3C{-}C_\alpha H{=}C_\beta H_2$), namely, $-CH_3$, $-C_\alpha H$, and $-C_\beta H_2$, are given in Table 1. The global softness (S) values for different radicals, electronegativities (χ), and condensed to atom softness [s^0(X)] values for the radical atom that takes part in hydrogen abstraction (i.e., the oxygen atom in OH and the carbon atom for other radicals) are also given in Table 1. Our calculated softness and electronegativity values for radicals follow almost the same trend as observed from the experimental values.[40] First we consider the hydrogen abstraction by different radicals from methane. Since the substrate is fixed (CH_4), the ease of hydrogen abstraction should depend only on the reactivity of the radical. Hydrogen abstraction can be considered easier when the corresponding barrier height is lower. It is apparent from the results in Table 1 that *there is no correlation between the global softness* (S) *for radicals and the barrier heights for hydrogen abstraction*. For example, the hydrogen abstraction reaction between CH_4 and the C_2H radical has the lowest barrier height, but the C_2H radical is neither the softest nor the hardest radical among the group. However, electronegativity of the attacking radicals has a correlation with the classical barrier heights for hydrogen abstraction from different substrates. The greater the electronegativity of the radical the easier the abstraction of hydrogen from substrates. Thus C_2H radical with the highest electronegativity value of 8.21 eV has the lowest barrier for hydrogen abstraction both from methane and propene, whereas C_2H_5 has the lowest value of electronegativity (3.45 eV) and accordingly the highest barrier height for hydrogen abstraction (see Table 1) both from methane and propene. In fact, for C_2H radical, the reaction barrier is very low and even barrierless for hydrogen abstraction from the $-CH_3$ site of propene. Figure 2A displays the correlation between electronegativity and classical barrier height for hydrogen abstraction from CH_4. For C_2H, the barrier height is somewhat lower than that expected from its electronegativity. Although the correlation is far from perfect, there is a clear trend that the barrier height tends to decrease with the increase in electronegativity of the radical. Thus *the more electronegative the attacking radical is, the lower the barrier height for hydrogen abstraction is*.

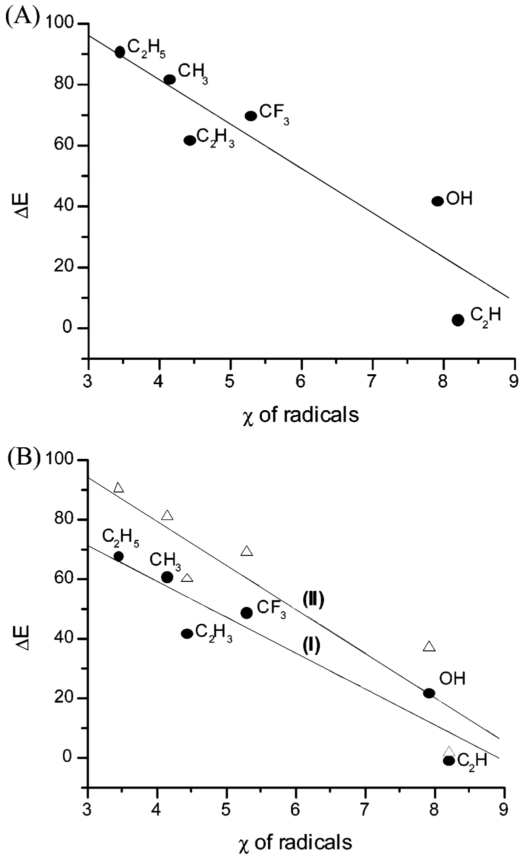

Figure 2. Plot of the classical barrier heights (kJ/mol) for hydrogen abstraction against electronegativity (χ in eV) for radicals: (A) for CH_4 and (B) for the $-CH_3$ site (I) and C_α site (II) of propene ($H_3C{-}C_\alpha{=}C_\beta H2$).

A similar relation has also been observed between the electronegativity of different attacking radicals and the classical barrier heights for hydrogen abstraction from the three different sites of propene. Figure 2B displays such linear correlation between the electronegativity of radicals and the classical barrier heights for hydrogen abstraction from the $-CH_3$ and C_α sites (see Figure 1) of propene. The same for the C_β site is not presented in the figure because it follows the same trend (see Table 1) as the C_α site. Now, among the three possible hydrogen abstraction sites of propene, hydrogen abstraction from the $-CH_3$ group is the easiest, with its much lower barrier than the other two channels (from the C_α and C_β sites). This is because of the much lower C−H bond dissociation enthalpy (D^0_{298K}) for the C−H bonds in the $-CH_3$ group of propene than the C−H bond for the two doubly bonded carbon atoms. For example, the D^0_{298K} value for the allylic C−H bond in the $-CH_3$ group of propene is 362.0 ± 8.8 kJ/mol, whereas the D^0_{298K} value for the same bond in C_2H_4 amounts to 465.3 ± 3.4 kJ/mol.[41]

The local softness of the radical center [s^0(X), Table 1] that is directly involved in hydrogen abstraction can also be an important reactivity parameter. The softness value is lowest for the carbon atom of C_2H (1.028) and highest for the carbon atom of CH_3 (3.207). Interestingly, hydrogen abstraction by C_2H has also the lowest barrier, as mentioned before. In fact, the data in

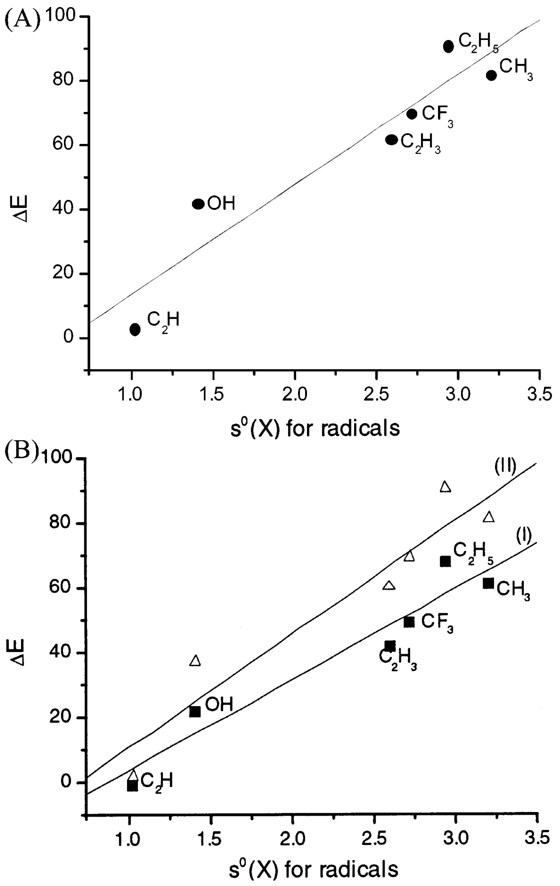

Figure 3. Plot of the classical barrier heights (kJ/mol) for hydrogen abstraction against the local softness of radical attack (s^0) for the radical centers of different radicals: (A) for CH_4 and (B) for the $-CH_3$ site (I) and C_α site (II) of propene ($H_3C-C_\alpha H{=}C_\beta H_2$).

Table 1 show that the barrier height tends to increase with the increase in softness of the attacking atom (X) of the radical. Only in the case of CH_3 and C_2H_5, the barrier heights are found to be in the reverse order than that expected from the s^0 value of the carbon atom. Figures 3(A) and (B) show the correlation between the barrier heights for hydrogen abstraction from methane and from the $-CH_3$ and C_α sites of propene (see Figure 1) and the s^0(X) values of the atoms in different radicals (i.e., the oxygen atom in OH and the carbon atom for other radicals) that take part directly in hydrogen abstraction. Once again, a clear pattern can be observed from these figures that *the harder the attacking radical center, the easier the hydrogen abstraction*. This is clearly opposite to that expected for addition reaction, where softer atoms should interact favorably. For all the radicals, the barrier height is lower for hydrogen abstraction from the $-CH_3$ group of propene than from CH_4. It was demonstrated before that there is a qualitative correlation between the hardness and the barrier height for hydrogen abstraction from saturated hydrocarbons.[42] The lower the hardness (i.e., greater softness) value of the substrate, the lower the barrier height. The softness values for CH_4 and propene are 1.52 and 2.15 au^{-1}, respectively. The higher softness of propene might be the reason for its lower hydrogen abstraction barrier, which is also reflected in the much lower D^0_{298K} value for the allylic C$-$H bond in propene than that in CH_4 (439.3 kJ/mol).[41]

B. Addition to C=C Double Bonds. There are two important aspects for the radical addition reactions to C=C bonds, namely: (i) for a particular substrate, how the barrier to addition changes with the change of radical and (ii) the regiochemistry of the addition reaction. In general, depending upon the substituents attached to the carbon atoms, the addition of a radical to one of the doubly bonded carbon atoms is generally preferred over the other. This introduces regioselectivity in addition reactions and the direct manifestation of it can be observed from the barrier to addition. It is known that free radical addition to unsaturated carbon atoms generally follows anti-Markovnikov orientation and the radical goes to the carbon that already holds the greater number of hydrogens.[43] This orientation of addition has been explained from the stability of the resulting radical after the addition. Table 2 shows the calculated classical barrier heights and the ZPE corrected barrier heights for the addition of different radicals to the two doubly bonded carbon atoms (C_α and C_β) of propene. The TS for the addition of C_2H radical to propene could not be determined and it appeared that the reaction was barrierless. The barrier for the addition to the β-carbon atom is found to be 2$-$9 kJ/mol lower than the addition to the α-carbon. Thus addition of radicals to the β-carbon atom of propene is easier and this correlates with the fact that the softness value for the β-carbon (1.393) is much higher than that for the α-carbon (0.377). As shown by Ponti,[25] higher softness values for the interacting atoms result in a greater negative value of the change in grand potential ($\Delta\Omega$) due to bond formation. Therefore, the carbon atom (β-carbon) with the higher softness value should be more susceptible to radical attack.

TABLE 2: Classical Barrier Heights (kJ/mol) and the Same with Zero Point Energy Corrections (within bracket) for the Addition of Different Radicals to the Two Doubly Bonded Carbon Atoms (see Figure 1) of Propene

	radical					
	OH	CH_3	CF_3	C_2H^a	C_2H_3	C_2H_5
C_α	-2 (5)	43 (52)	18 (19)		28 (33)	46 (53)
C_β	-4 (3)	34 (43)	10 (11)		21 (25)	38 (45)

[a] The TS could not be located.

For a particular substrate and site of addition, the change in barriers to addition for different radicals should be characteristic of the reactive properties of the radicals. On the onset, one can easily think of two such reactive parameters, namely, electronegativity of the radical (a global property) and the softness of the radical atom [s^0(X) for the oxygen atom of OH and for the carbon atoms of other radicals in Table 1] taking part in bond formation. It is evident from Figure 4(A) that there is no meaningful correlation between s^0(X) values for different radicals and the barrier heights. However, a certain correlation between the barrier heights for addition and the electronegativity of the radicals seems to exist, as shown in Figure 4B. *The barrier height for radical addition decreases with the increase in electronegativity of the radicals*. It is clear from Table 1 that the chemical potential (negative of electronegativity) values for radicals are much lower than that of propene (-3.24 eV). Thus increasing electronegativity of radicals results in greater net electron flow from propene to radicals during addition reactions and, thereby, decreases the barrier height. The OH radical is slightly off from the correlation line of the four radicals with carbon as the interacting atom. This is no doubt due to the different nature of the interacting atom. It is apparently not meaningful to compare the local softnesses of two different radical centers.

C. Substituted Propenes. To verify the observations further, we studied the hydrogen abstraction and addition reactions of substituted propenes ($H_3C-CH{=}CHF$, $H_3C-CH{=}CHCl$, $H_3C-CH{=}CHNH_2$) with two different radicals, OH and CH_3. The reactivity parameters and barrier heights for abstraction and radical addition reactions are given in Table 3. Hydrogen

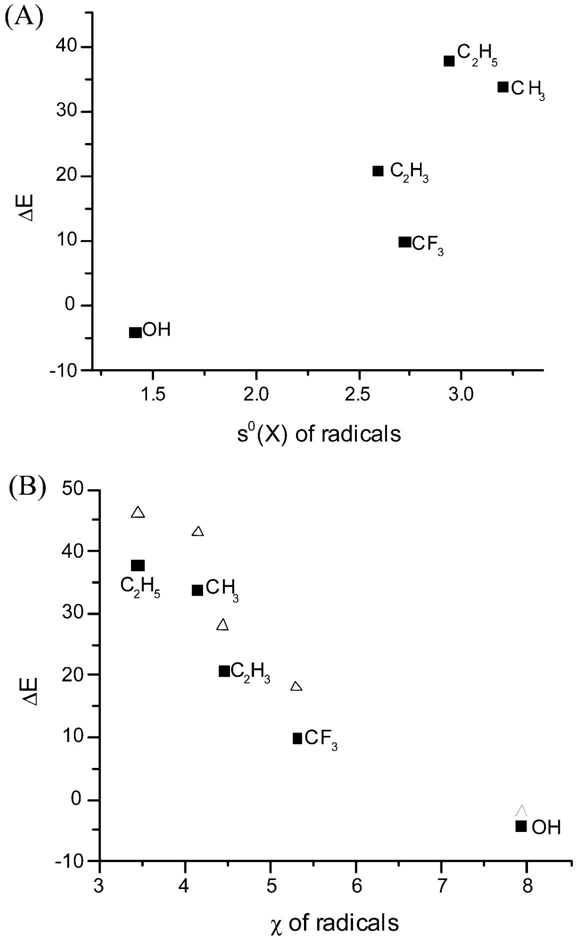

Figure 4. (A) Classical barrier heights (kJ/mol) for different radical addition to the C_β carbon atom of propene (Figure 1) are plotted against local softness values for the radical center; (B) the barrier heights (kJ/mol) for the additions to C_α (open triangles) and C_β (black squares) carbon atoms of propene are plotted against electronegativity of radicals (B).

TABLE 3: Global Softness (S, a.u.$^{-1}$), Atomic Softness for Radical Attack for the Two Doubly Bonded Atoms of Substituted Propylene [s^0], and Classical Barrier Heights for Hydrogen Abstraction and Radical Addition Reaction of Substituted Propene with OH and CH_3 Radical

				barrier heights, kJ/mol[a,b]			
				addition reaction		H-abstraction by	
system	S	atom	s^0	OH	CH_3	CH_3	OH
C_3H_6	2.15	C_α	0.377	−2 (5)	43 (52)	81 (77)	37 (29)
		C_β	1.393	−4 (3)	34 (43)	90 (86)	47 (38)
C_3H_5F	2.13	C_α	0.652	−4 (4)	41 (50)	84 (81)	45 (37)
		C_β	0.899	−5 (2)	38 (46)	88 (86)	53 (45)
C_3H_5Cl	2.30	C_α	0.804	−5 (2)	36 (45)	77 (74)	40 (32)
		C_β	0.431	4 (10)	42 (51)	79 (77)	44 (37)
$C_3H_5N\ H_2$	2.44	C_α	0.583	−18 (−10)	38 (46)	87 (83)	39 (31)
		C_β	0.068	−17 (−11)	46 (55)	85 (81)	37 (29)

[a] The quantities within bracket are the barrier heights after zero-point energy corrections. [b] The barrier heights for hydrogen abstraction by OH radical from the $-CH_3$ site of C_3H_6, C_3H_5F, C_3H_5Cl, and $C_3H_5NH_2$ are 15, 15, 15, and 4 kJ/mol, respectively. The barrier heights for hydrogen abstraction from the $-CH_3$ site of C_3H_6, C_3H_5F, C_3H_5Cl, and $C_3H_5NH_2$ by CH_3 radical are 58, 59, 57, and 53 kJ/mol, respectively.

abstraction by OH radical always has a much lower barrier than that for CH_3 radical. Again, this can easily be explained from the higher electronegativity of the OH group and lower softness for the interacting oxygen atom than those for the CH_3 group (see Table 1). Hydrogen abstraction from the $-CH_3$ group is much easier than that from the two doubly bonded carbon atoms of propenes. We observed that the hydrogen atoms in the CH_3 group of propene have much higher s^0 values than the hydrogens attached to the two doubly bonded carbon atoms. For example, the atomic softness, s^0, value for the allylic hydrogen atoms (0.320) of the methyl group of propene is much higher than the hydrogen atoms (highest value is 0.127) attached to the two doubly bonded carbon atoms. The same observations were made for all the substituted propenes. Nevertheless, we could not find any quantitative correlation between the s^0 values for the abstracted hydrogen and the corresponding barrier heights for hydrogen abstraction from substituted propenes. Thus the s^0 value for the abstracted hydrogen atom does not have any major role in determining the ease of reaction.

In propene and substituted propenes ($H_3C-CH=CHX$, X = F, Cl, NH_2) the two doubly bonded carbon atoms are not equivalent and this introduces interesting regiochemistry for radical addition reactions. As evident from Table 3, addition to one of the doubly bonded carbon atoms has a lower barrier height than addition to the other. The reaction channel with lower barrier height is likely to be dominating. Thus the β-carbon should be the preferred site of radical attack for C_3H_6 and C_3H_5F, whereas the α-carbon should be the favored radical addition site for C_3H_5Cl and $C_3H_5NH_2$. Therefore, radical additions to C_3H_6 and C_3H_5F follow the usual anti-Markovnikov orientation, whereas the radical additions to C_3H_5Cl and $C_3H_5NH_2$ follow Markovnikov orientation. This feature shows an interesting regiochemistry in these radical addition reactions. To rationalize this observed regioselectivity, we have calculated the softness for radical attack (s^0) for both the doubly bonded carbon atoms of propene. Now for a particular radical and substrate, the carbon atom with higher s^0 value should be the preferred site for radical attack, because a higher s^0 value results in a greater negative grand potential change for the formation of the new bond.[25] Table 3 shows that for C_3H_6 and C_3H_5F the β-carbon has the greater s^0 value. On the other hand, the α-carbon has the greater s^0 value for C_3H_5Cl and $C_3H_5NH_2$. It is, therefore, expected that the β-carbon should be the preferred site of radical attack for C_3H_6 and C_3H_5F, whereas the α-carbon should be the favored site for C_3H_5Cl and $C_3H_5NH_2$. The barrier heights in Table 3 demonstrate the same regioselectivity for radical addition. Overall, *the s^0 values for different sites could be used to determine the most favored site for radical attack when the substrate has more than one potential site*. The barrier height for radical addition is always found to be substantially lower for OH radical in comparison to CH_3 radical. As discussed before, the higher electronegativity of the OH group and lower s^0 value for the oxygen atom in OH make its addition easier than that of CH_3 radical. We must point out that although s^0 values allow us to qualitatively explain the observed regioselectivity for radical additions, we could not find any DFT-based descriptor that could be correlated well with the barrier heights.

4. Summary and Conclusions

We have made a systematic analysis for the hydrogen abstraction reactions of CH_4 and propene with a series of radicals. It is observed from our study that electronegativity of the radical has an important role in determining the ease of hydrogen abstraction from a substrate. In general, *the more electronegative the attacking radical, the lower the barrier height for hydrogen abstraction from a substrate*. Similarly, the local softness of the atom in the radical directly involved in hydrogen abstraction has been found to have an inverse correlation with the barrier height for hydrogen abstraction. *The* *harder the attacking atom of the radical, the easier the hydrogen abstraction is*. This is clearly opposite to that expected for the addition reaction, where the softer atom interacts more favorably. In the case of radical addition to C═C, no quantitative correlation between barrier heights and reactivity descriptors could be observed. Of course, electronegativities of radicals appear to have a qualitative correlation with the barrier heights for addition reactions. *The barrier height tends to decrease with the increase in electronegativity of the radical.* The regiochemistry for radical addition to the doubly bonded carbon atoms can be resolved from the s^0 values of the two carbon atoms. The carbon atom with the higher s^0 value is always found to be the preferred site for radical attack. Thus, *s^0 values for different sites could be used to determine the most favored site for radical attack when the substrate has more than one potential site*. Although the relations observed between the barrier heights for hydrogen abstraction by radicals (also for radical addition reactions) and the different reactivity parameters are definitely not quantitative and the studies are not exhaustive, they do exhibit a clear trend that helps the interpretation and understanding of the mechanism of these two classes of radical reactions.

A particular difficulty in correlating the local softness for radical attack (s^0) with calculated energy barriers likely arises from the fact that this quantity is not well defined. While the local softness for nucleophilic (s^+) and electrophilic (s^-) attacks has a clear chemical meaning, that for radical attack, defined as the average of s^+ and s^- values, is ambiguous. Another way of evaluating this parameter without referring to the anionic and cationic states is highly desirable.

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Supporting Information Available: Figure-S1 showing the correlation between the BHandHLYP/6-311G(d,p) and CCSD(T)/6-311++G(d,p) calculated barrier heights for hydrogen abstraction from methane and propene by various radicals (OH, CH_3, CF_3, C_2H_3, and C_2H_5). This material is available free of charge via the Internet at http://pubs.acs.org.

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